# Beam Losses on the Tevatron Ramp

Wolfram Fischer
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Typically 10-15% of the protons and antiprotons are lost in the Tevatron during the ramp. Without these losses, the luminosity would be about 25% higher. In addition, the vertical emittances of both protons and antiprotons are increased on the ramp. The losses can be large enough to lead to a quench.

The table below summarizes this for the 21 operational stores from store numbers 1356 through 1501. Fig. 1 shows a ramp with a typical beam loss over the first 15 seconds of the ramp. They amount to 8 to 10% of the initial intensity. Below possible reasons for the beam loss are discussed, including orbits, tunes, chromaticities, correlations with initial intensity, emittances and bunch length, reduction in bucket area, and coherent longitudinal oscillations.

**Table 1 – Proton and antiproton intensity and emittance change for 21 ramps (1356 through 1501), in percent.**

| | **Protons** | **pbars** | **protons** | | **pbars** | |
|---|---|---|---|---|---|---|
| | D**I/I** | D**I/I** | $De_y/e_y$ | $De_x/e_x$ | $De_y/e_y$ | $De_x/e_x$ |
| **mean** | **-10.0%** | **-15.2%** | **11.4%** | **-5.9%** | **9.5%** | **-5.6%** |
| **rms** | **3.2%** | **7.8%** | **8.9%** | **28.3%** | **14.4%** | **26.2%** |

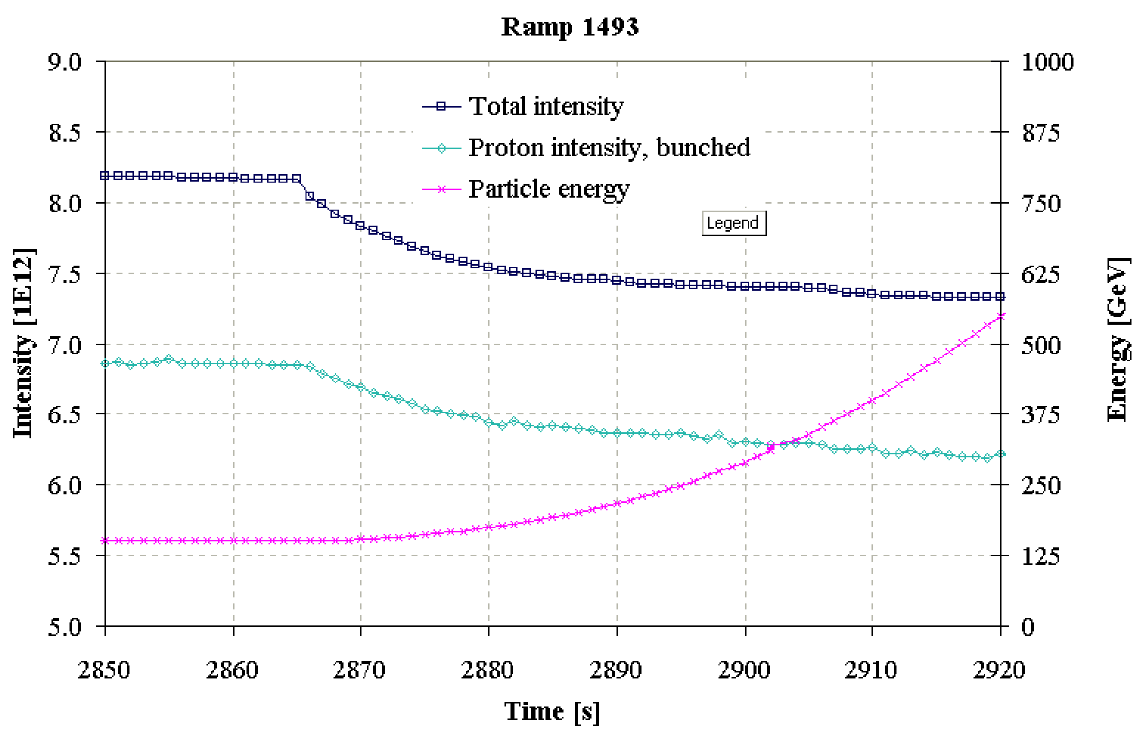


**Figure 1 – Typical intensity drop during the first 15 seconds of the ramp.**

## 1. Orbit changes during the ramp

Orbit changes along the ramp are an unlikely reason for the observed beam losses. First, the deviations from the central orbit decrease along the ramp since the helix amplitudes are decreased. Second, an orbit problem should resemble a scraper that moves into the beam. In this case, there is a sudden loss followed by a reduction in the beam lifetime. This is not consistent with the beam loss pattern observed. Third, after orbit improvements the losses remained.

## 2. Tunes during the ramp

The tunes are set to $(Q_x,Q_y) = (20.575,20.585)$ before the ramp starts. A measurement of the tunes along the ramp is shown in Fig. 2 without and with a frequency offset of 40 Hz. The measurement was performed on the central orbit with uncoalesced beam. The vertical tune drops over the first 15 seconds while the horizontal one stays relatively constant. At 20.5714 is a $7^{th}$ order resonance, which may deteriorate the lifetime. Tune changes on the ramp could not eliminate the losses.

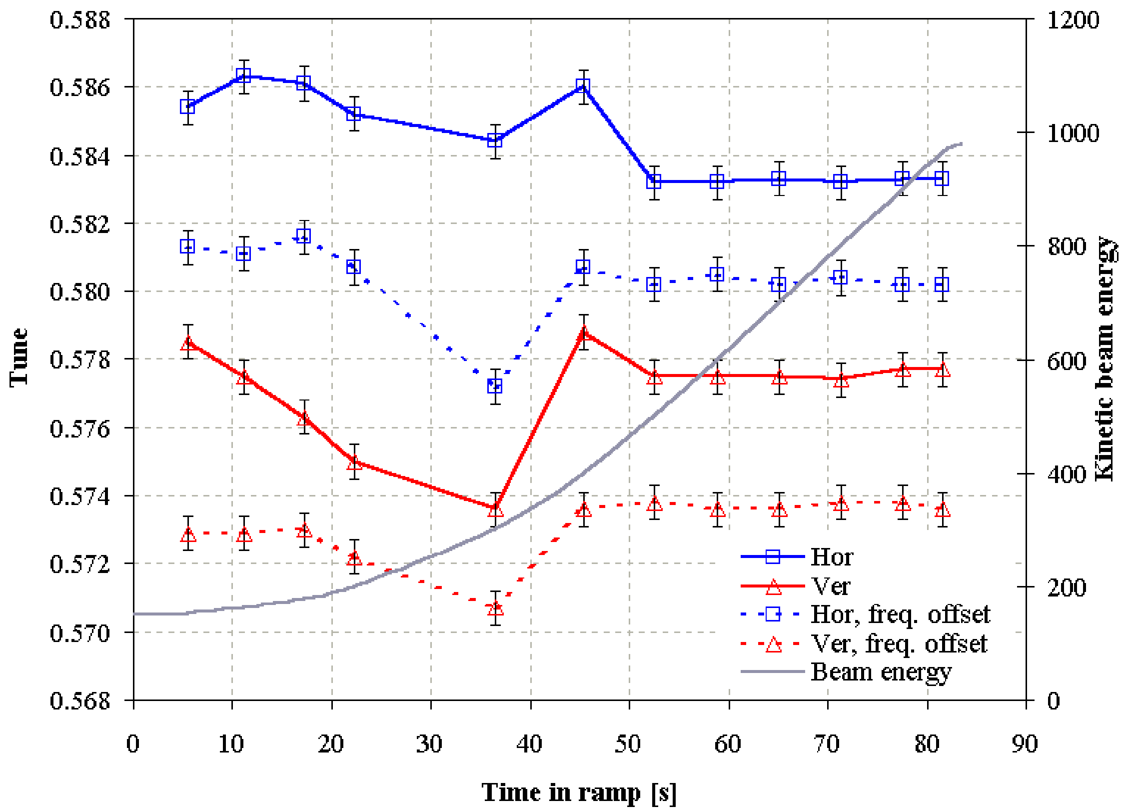


**Figure 2 – Tunes along the ramp on the central orbit without and with a frequency offset of +40 Hz (07/13/2002, R. Moore).**

### 3. Chromaticities during the ramp

The chromaticities are set to $(\xi_x,\xi_y) = (+8,+8)$ at injection. Fig. 3 shows a chromaticity measurement along the ramp. At the beginning of the ramp, the chromaticities may reach values as large as 15 – 20. Small changes in the chromaticity in both planes (2-4 units) did not reduce the losses (see below for implemented changes). Small chromaticities may also lead to transverse instabilities.

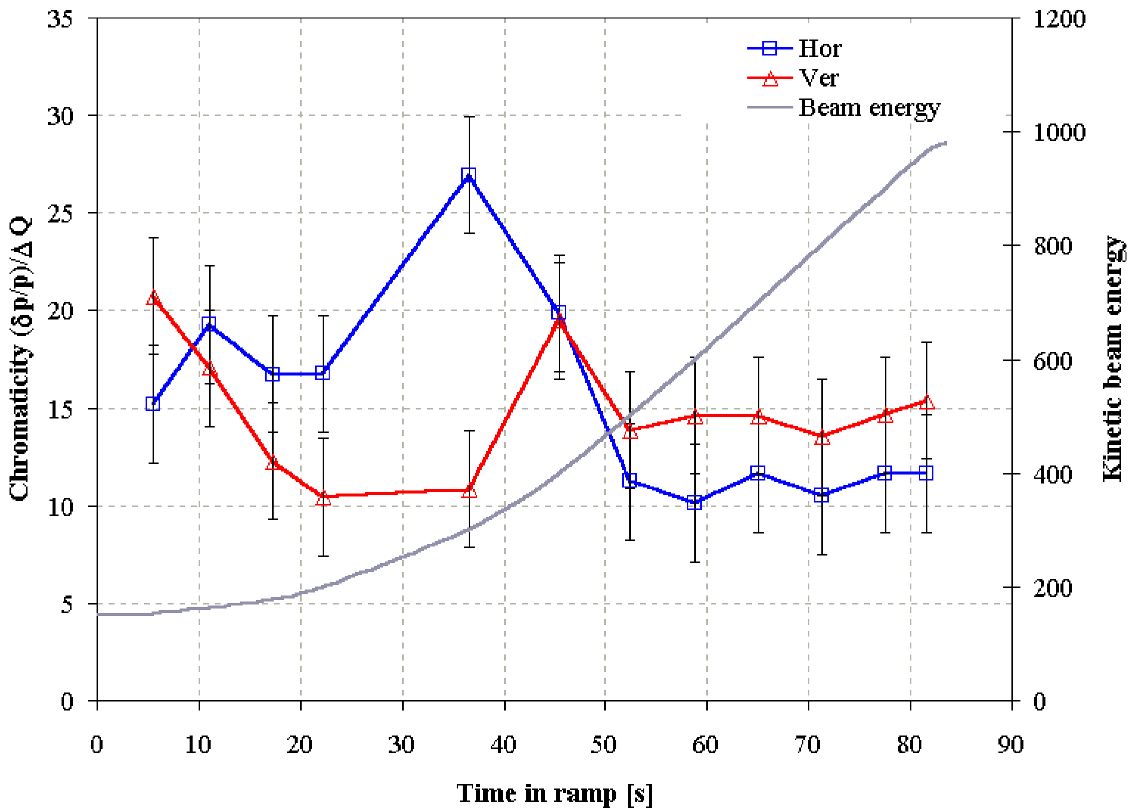


**Figure 3 – Chromaticities along the ramp near the central orbit (07/13/2002, R. Moore).**

| *07/02/2002 T. Sen, W. Fischer* | *07/14/2002 B. Hanna, Y. Alexahin* |
|---|---|
| 153 GeV Cv 34→30 | 153 GeV Ch 51→49 |
| 162 GeV Cv 37→35 | 162 GeV Ch 53→48 |
| | 180 GeV Ch 49→46 |
| | 200 GeV Ch 51→48 |

After 05/21/2001 the chromaticities on the ramp were increased by several units to avoid coherent instabilities, which increased the antiproton emittances. In Fig. 4 and Fig. 5 a difference in the beam loss can be seen: with increased chromaticities the losses along the ramp increase.

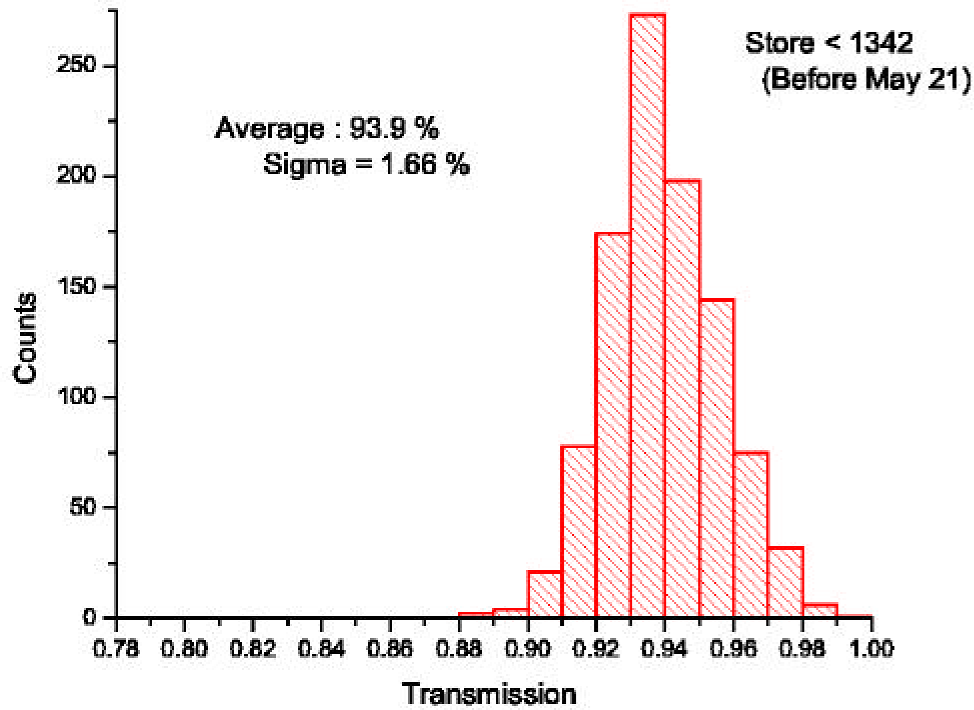


**Figure 4 – Transmission on the ramp before 05/21/2002 (courtesy P. Lebrun).**

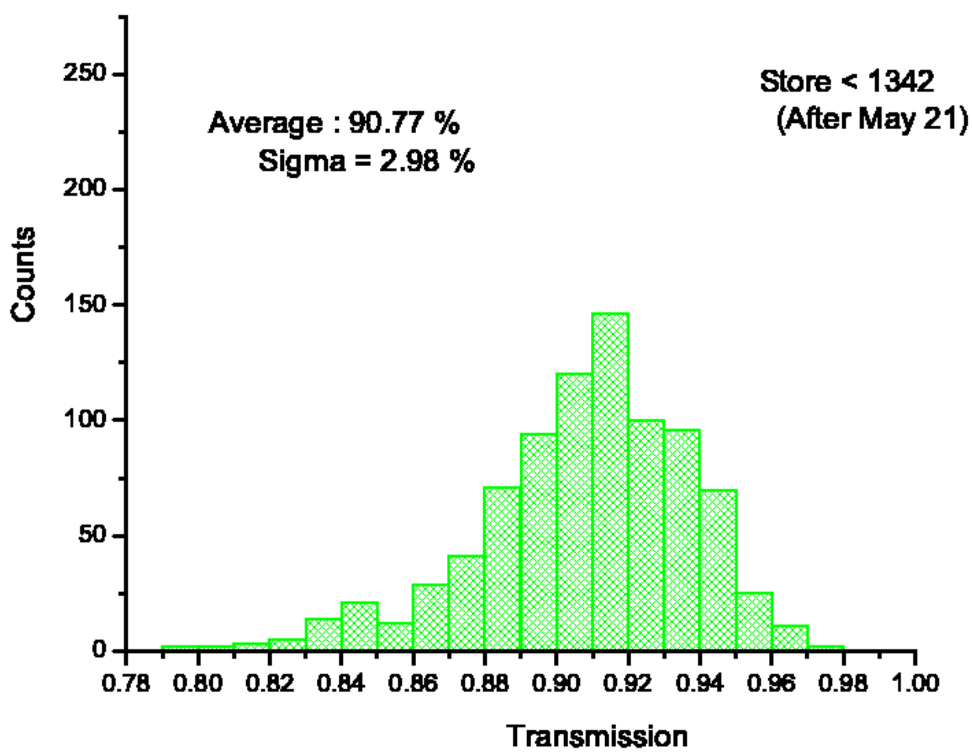


**Figure 5 – Transmission on the ramp after 05.21/2002 (courtesy P. Lebrun).**

On the helix particles sample the nonlinear field regions. The strengths of lattice driven resonances increase with amplitude. At injection, the rf buckets are almost filled (see below) and a chromaticity of 20 together with a maximum momentum deviation of $(\delta p/p)_{max}$ = 0.001 leads to a tune total spread of 0.04, and a tune modulation at the synchrotron frequency with a maximum amplitude of 0.02. Furthermore, particles with large momentum deviations, have smaller modulation frequencies, which This is very likely to cause beam losses[1] and modulation depth smaller by an order of magnitude were seen to have visible damaging effects.

## 4. Correlation of losses with initial intensity, emittances and bunch length

The correlation of beam losses with the initial bunch intensity, emittances and bunch length is shown in Figs. 6 – 8 for the store numbers 1224 through 1556[2] (P. Lebrun). There is little correlation with initial intensity, emittance or bunch length over the operational intervals.
On a test ramp three bunches with intensities different by about a factor 3 between the lowest and highest intensity were accelerated (see Fig. 9). However, the three bunches also had different bunch length; the higher the bunch intensity, the longer the bunch. The beam losses were14%, 10% and 8% for the highest, medium and lowest intensity bunch respectively.
An attempt was made to accelerate three bunches with different intensities but the same bunch length. For this high intensity bunches were scraped down vertically. A ramp was prevented due to a cryo interlock. This test would have clarified whether the losses are longitudinal or transversal. A test ramp with uncoalesced proton beam on the proton helix showed that beam with low momentum spread can be ramped without loss (see Fig. 10).

## 5. Beam loss out of rf buckets

The rf buckets are almost full at injection (Fig. 11, bucket length is 18 ns). With increasing energy, the bucket area first decreases and then increases again. The initial decrease in the moving bucket area may lead to losses. Fig. 13 shows the moving bucket area at the beginning of the ramp. From the beginning of the ramp up to 10 seconds into the ramp the bucket area decreases by only 2.5%, which cannot explain the beam loss observed.
Coherent longitudinal oscillations, observed at all energies, may also contribute to the beam losses along the ramp[3]. However, on the central orbit they do not cause any measurable loss at 150 GeV. These oscillations are more pronounced for uncoalesced beam (Fig. 14).

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[1] See for example: T. Satogata et al, PRL 68 (1992); F. Zimmermann, Ph.D. Thesis, Hamburg University (1993); O. Brüning, Ph.D. Thesis, Hamburg University (1994); W. Fischer, Ph.D. Thesis, Hamburg University (1995); W. Fischer, M. Giovannozzi and F. Schmidt, “Dynamic Aperture Experiment at a Synchrotron”, Phys. Rev. E, Vol. 55, Number 3, p. 3507 (1997).
[2] The used stores are 1224, 1226, 1229, 1240, 1242, 1243, 1253, 1257, 1258, 1260, 1280, 1285, 1287, 1383, 1392, 1393, 1396, 1401, 1288, 1289, 1291, 1303, 1305, 1307, 1309, 1313, 1328, 1329, 1332, 1333, 1335, 1337, 1339, 1340, 1356, 1359, 1365, 1367, 1369, 1434, 1443, 1448, 1462, 1464, 1480, 1482, 1486, 1518, 1526, 1528, 1530, 1563, 1565.
[3] J. MacLachlan, private communication.

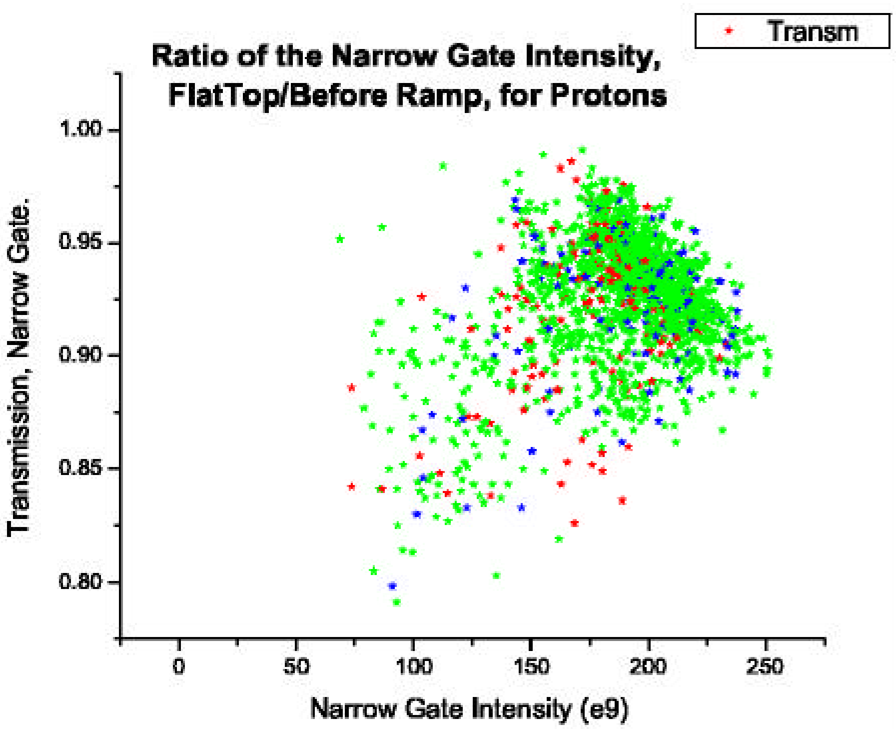


**Figure 6 – Proton transmission through the ramp as a function of initial proton bunch intensity for shots 1224 through 1565 (courtesy P. Lebrun).**

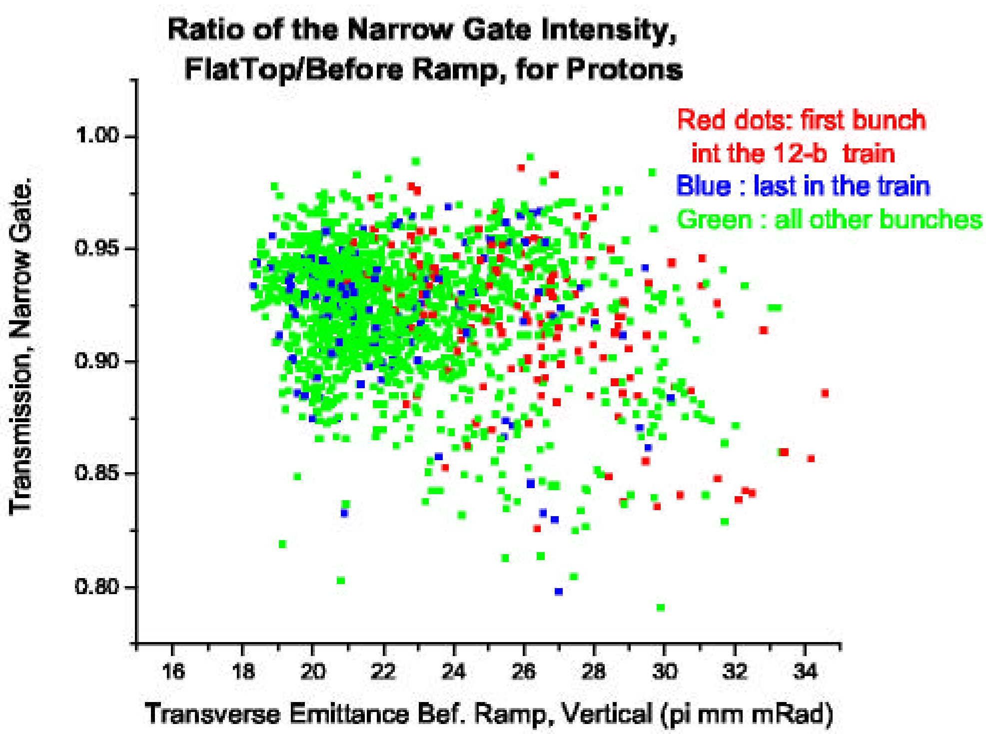


**Figure 7 – Proton transmission through the ramp as a function of intial vertical emittance for stores 1224 through 1565 (courtesy P. Lebrun).**

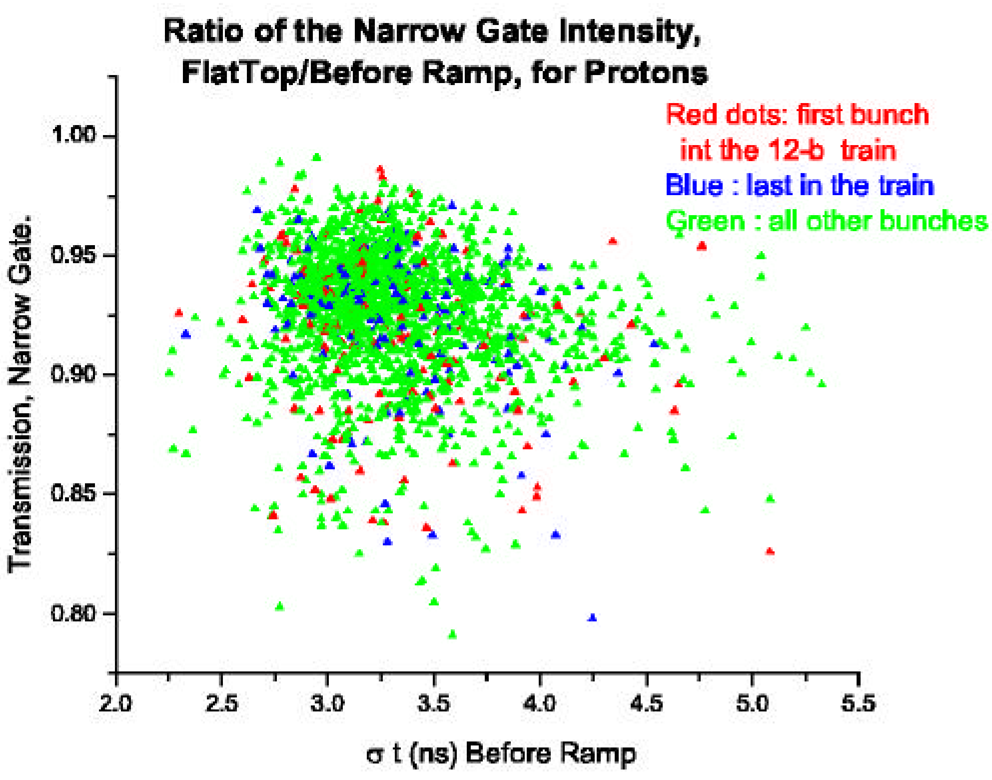


**Figure 8 – Proton transmission through the ramp as a function of intial bunch length for stores 1224 through 1565 (courtesy P. Lebrun).**

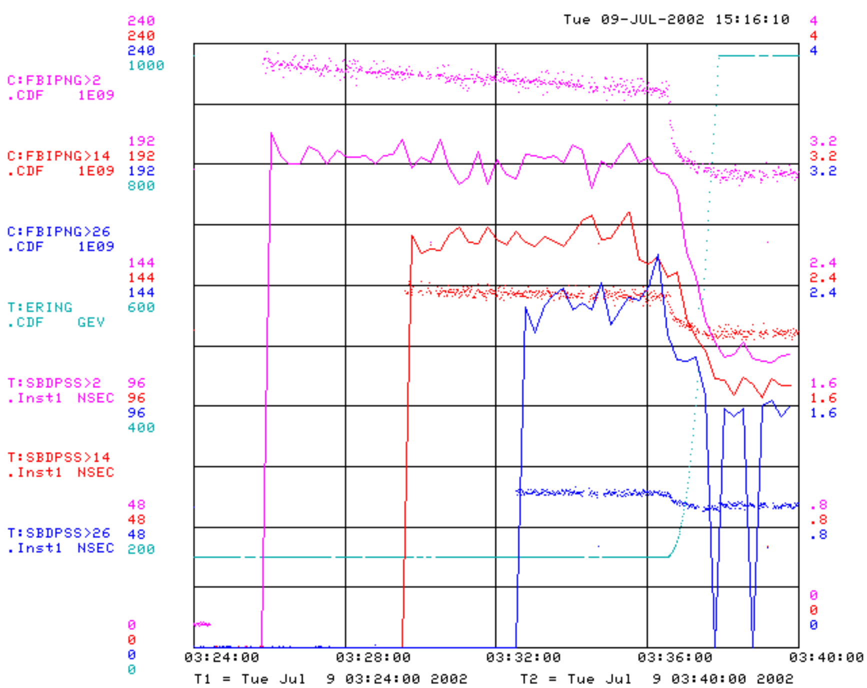


**Figure 9 – Particle loss at the beginning of the ramp for three bunches with different intensities and bunch lengths. The losses increase for bunches with higher intensity, which also have greater bunch length (courtesy V. Shiltsev).**

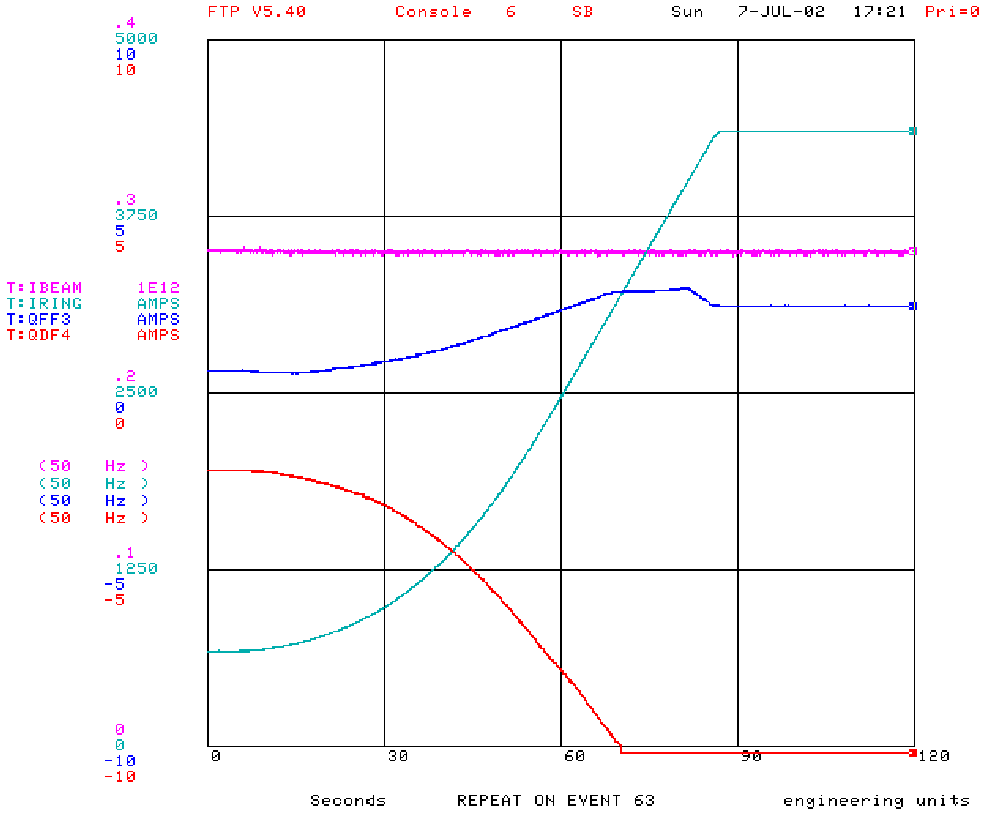


**Figure 10 – Loss free proton ramp with uncoalesced beam on proton helix (courtesy B. Hanna).**

## 6. Schottky Power During Ramp

At the beginning of the ramp the transverse Schottky power jumps in both transverse planes (see Fig. 15). The horizontal and vertical power is also strongly correlated suggesting substantial coupling along the ramp. The transverse Schottky power scales with the number of particles *N* and the relativistic beam *g* like

$$P \propto \frac{N}{b^2 g} \approx \frac{N}{g}$$

With the slow change of the beam energy at the beginning of the ramp the Schottky power should slowly decrease. The jump in the Schottky power is likely a sign of coherent motion that starts with the ramp.

## 7. Further losses

After 41 second into the ramp, at an energy of 375 GeV, a small loss of about 0.5% of the stored particles occurs, that can be observed on all ramps.

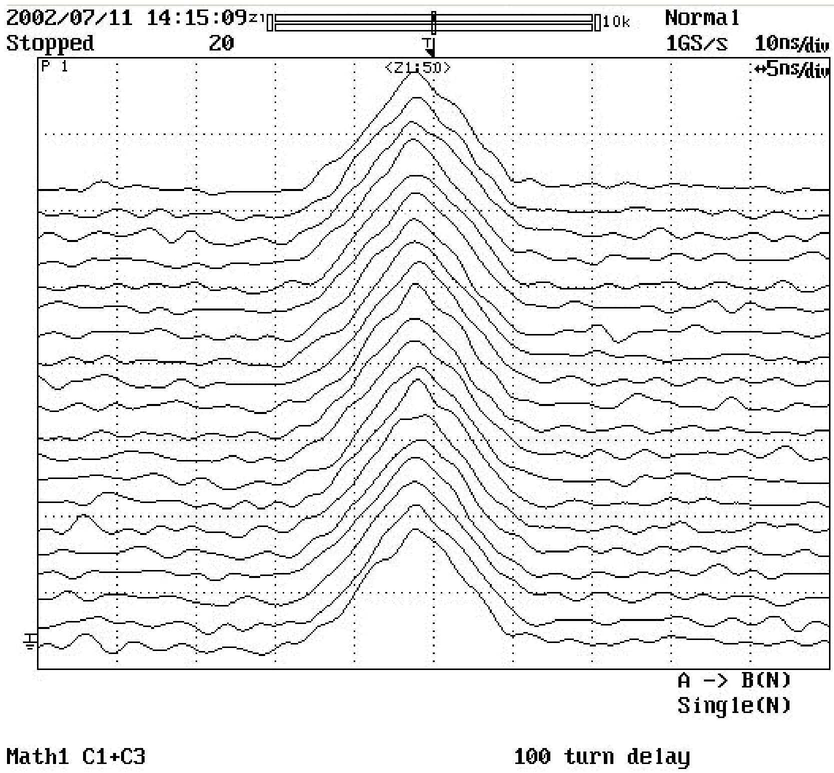


**Figure 11 – Longitudinal profiles of a single bunch at the beginning of the ramp (courtesy R. Moore).**

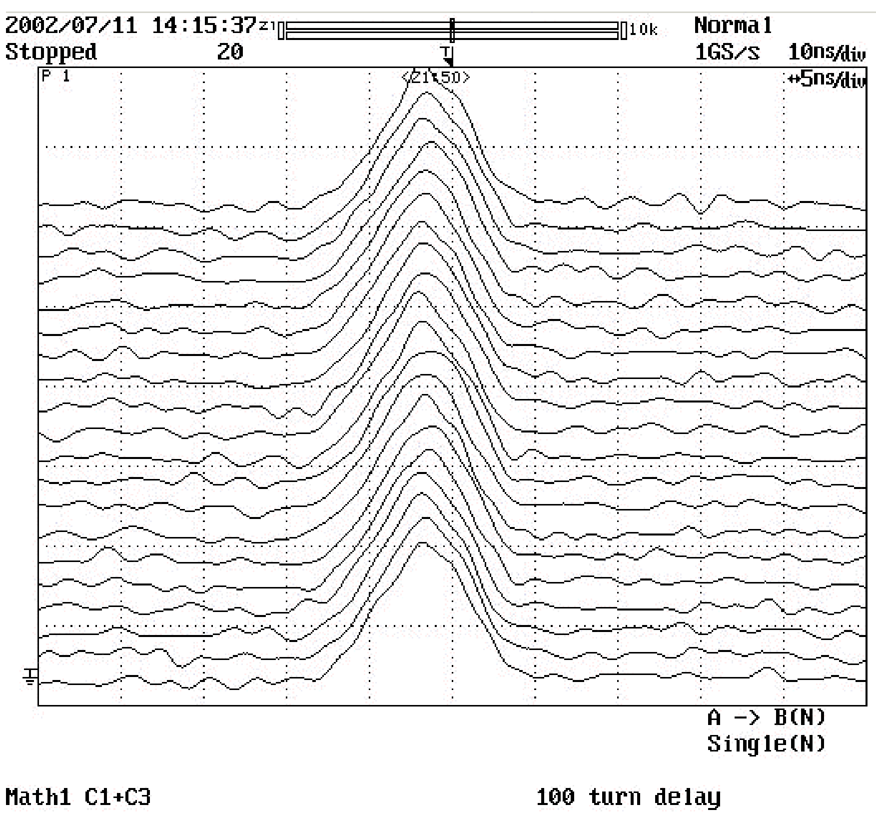


**Figure 12 – Longitudinal profiles of a single bunch around 550 GeV (courtesy R. Moore).**

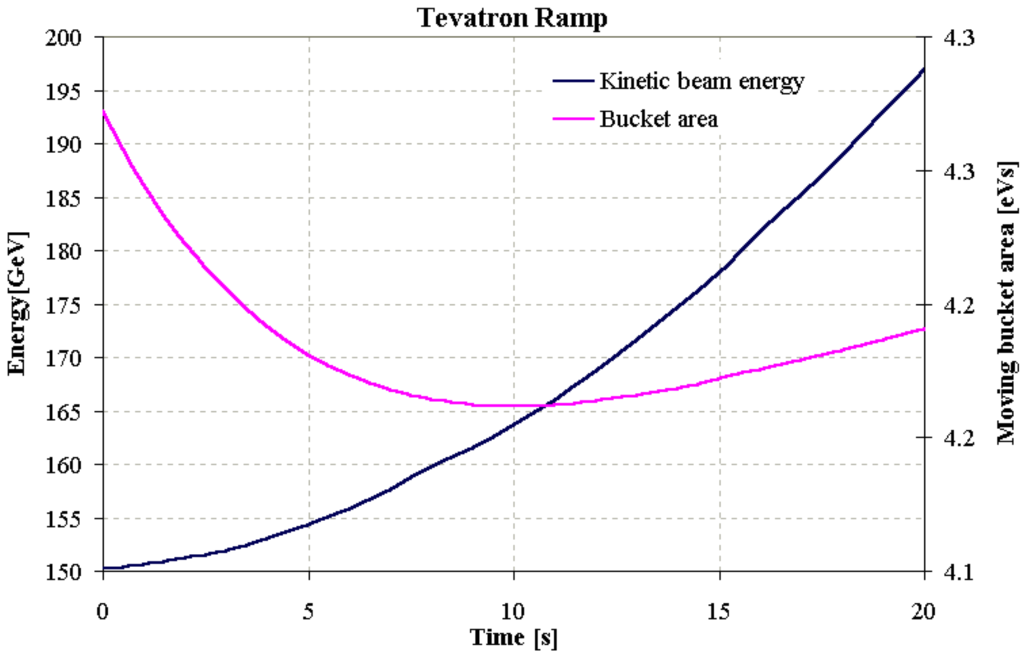


**Figure 13 – Beam energy and moving bucket area at the beginning of the ramp.**

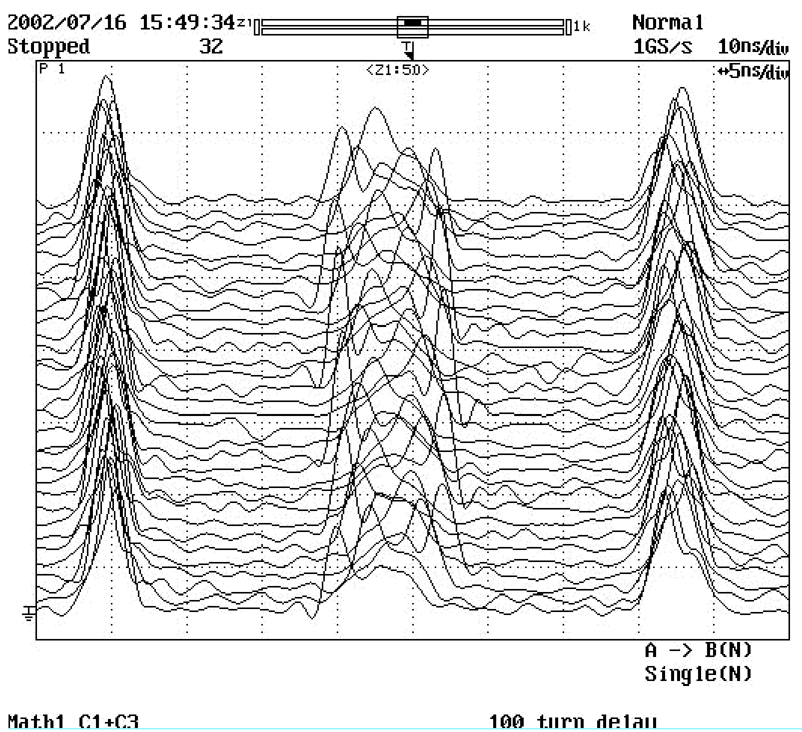


**Figure 14 – Coherent longitudinal oscillations at 150 GeV with uncoalesced beam (courtesy V. Balbekov and V. Lebedev).**

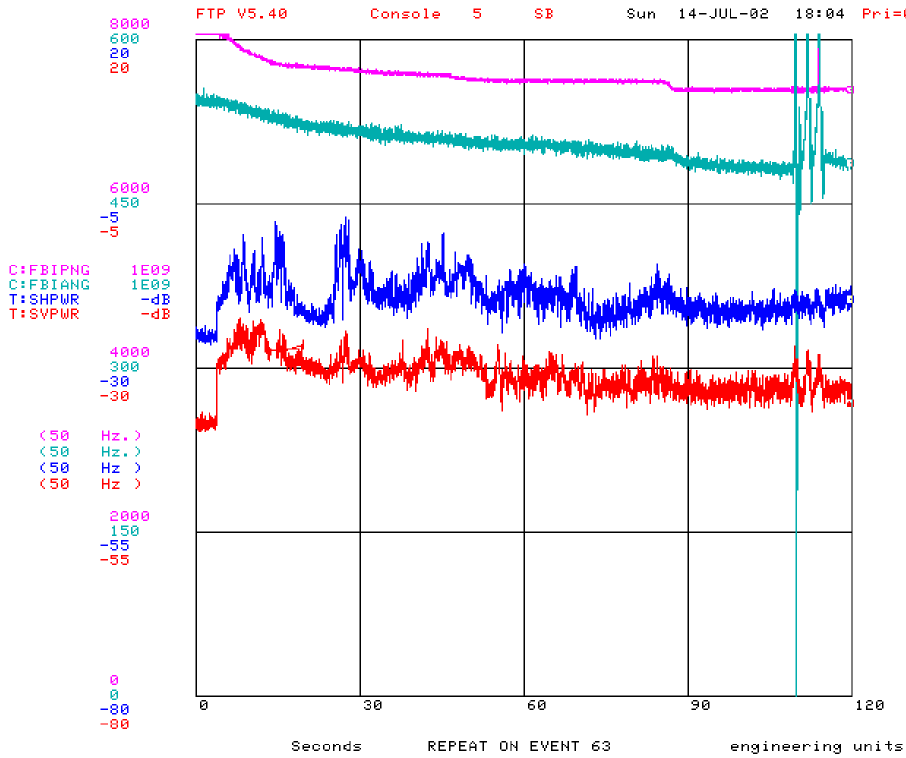


**Figure 15 – Schottky power from the horizontal (blue) and vertical (red) detector during the ramp (courtesy Y. Alexahin).**

## 8. Conclusions

Most likely, the particle losses at the beginning of the ramp are connected to the large chromaticities, which reach values as high as 15 – 20. Together with the momentum spread of $(\delta p/p)_{max} = 0.001$ this leads to a total tune spread of up to $\Delta Q \approx 0.04$. Through synchrotron motion transverse tunes are modulated at a frequency of $f_s \approx 100$ Hz with a modulation depth of up to $\Delta Q_m \approx 0.02$.
Operational experience indicates that the large tune spread, currently provided through the chromaticity, is needed to avoid transverse instabilities during the ramp. There are three ways to mitigate the beam loss problem:

(1) A reduction of the momentum spread $(\delta p/p)_{max}$ of the injected beam would reduce both, the tune spread and the tune modulation depth.

(2) Tune spread needed to suppress instabilities can also be provided by octupoles, which would allow reducing the chromaticity and thus the tune modulation depth. The implementation of this configuration had been tried and may be time consuming.

(3) A transverse damper system capable of suppressing the transverse instability would allow reducing the chromaticity.

For the analysis of beam losses during the ramp it would advantageous if tunes and chromaticities could be saved electronically for every ramp (for example at the break points). An envelope can be fitted to the synchrotron sidebands. This yields the tunes with a precision of better than 0.001, and the tune spreads, which are currently dominated by the chromaticity.

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